Improving Aerosol and Visibility Forecasting Capabilities Using Current and Future Generations of Satellite Observations

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LONG-TERM GOALS

Critical to climate and air quality studies, the analysis and prediction of atmospheric aerosol events are equally important for military applications. Accurate aerosol and visibility forecasts are of interest to DOD applications, especially the widespread and increased usage of optically-sensitive equipment and advanced electro-optical (EO) systems in military operations. In addition, recent DoD regions of conflict are also frequently inundated with dense aerosol events, such as the Middle-East. The long term goal for this project is to improve the Navy's aerosol forecasting capabilities through developing cutting-edge aerosol data assimilation schemes that use observations from passive and active satellite sensors at both product and radiance levels.

OBJECTIVES (abstract from proposal)

Critical to both military and civilian applications, the Navy Aerosol Analysis and Prediction System (NAAPS) is the worlds only truly operational global aerosol and visibility forecasting model. Recent studies indicate that the assimilation of satellite observations significantly improves NAAPS aerosol forecasting capability and reliability. To fully utilize the wide breadth and depth of various current satellite observations, and prepare for future reductions in aerosol sensing satellites over the next decade, we propose to construct a multi-channel, multi-sensor, and multi-task assimilation system to improve NAAPS forecasts for both current and future applications. The specific objectives are to:

1. Finalize over-land and over-ocean aerosol assimilation methods using operational data assimilation quality Moderate Resolution Imaging Spectroradiometer (MODIS) and Multiangle Imaging SpectroRadiometer (MISR) aerosol products, and develop a framework for considering current and future satellite aerosol products.

2. Develop forward models to enable a radiance assimilation capability by: 1) improving forecast performance over cloudy regions using the Ozone Monitoring Instrument (OMI) Aerosol Index; and 2) preparing for the post-MODIS/MISR era using the Geostationary Operational Environmental Satellite (GOES).

3. Improve model representations of aerosol vertical profiles and the accuracy of aerosol speciation in NAAPS through the use of a 3-D aerosol assimilation method and a generalized Angstrom exponent assimilation scheme.

4. Develop an improved 3-D parameterization for satellite observation and model forecasting error matrices using ground observations from the Aerosol Robotic Network (AERONET) and the Micropulse Lidar Network (MPLNET).

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APPROACH

High-quality, unbiased observations/retrievals are needed for improving numerical model predictions of atmospheric aerosol particle physical properties through data assimilation. However, as suggested from several previous studies [e.g. Shi et al., 2010], large uncertainties exist in satellite aerosol products. Diverging aerosol optical depth (AOD) values are observed among the most widely used aerosol products, such as MODIS and MISR. Consequentially, efforts are needed to critically evaluate current and future aerosol products for constructing data assimilation ready (or DA-quality) products. The focus of this first approach includes the careful examination of uncertainties in satellite aerosol products in relation to cloud contamination, aerosol microphysical bias, and biases in lower surface boundary conditions.

With the support from ONR, we have developed NAVDAS-AOD, which was initially designed to assimilate satellite aerosol optical depth data into NAAPS. A 3-D assimilation capability was later added, in order to assimilate aerosol vertical extinction profiles observed from Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP). Validation efforts suggested that with the use of both optical depth and extinction data from multi-sensor instruments including MODIS, MISR and CALIOP, both NAAPS analysis and forecasting skills can be significantly improved [e.g. Zhang et al., 2013]. Current efforts include exploring new methods for directly assimilating GOES satellite radiance and for exploring the possibility of including above cloud aerosol retrievals from OMI.

New and unexpected results have also been discovered through exploring research directions from the first two approaches. For example, with the support from this project, we developed a nighttime aerosol retrieval method last year [e.g. Johnson et al., 2013], representing one of the first attempts to estimate nighttime aerosol properties using a day-night band from Visible Infrared Imager Radiometer Suite (VIIRS). Following last year's efforts, new research highlights/directions will continue to be explored, all leading to improvements for satellite aerosol and/or aerosol data assimilation studies.

WORK COMPLETED

Collaborating with researchers from NRL (Dr. Jeff Reid, Dr. Edward Hyer, Dr. James Campbell, and Dr. Douglas Westphal), we have made successful progress toward our research goals. The research group from UND, funded by this project, published/submitted nine first-author and co-authored journal papers and eight conference presentations during the last fiscal year. Two other journal papers are ready for submission in the very near future. In addition, a coupled NAAPS-CRTM model has been developed for GOES radiance assimilation. A finer resolution NAVDAS-AOD system of 1/3°×1/3° (Latitude/Longitude) has also been developed and delivered for operational forecasts.

New discoveries:
Past and current aerosol assimilation efforts concentrated on assimilating satellite observations over cloud-free skies. Under cloudy skies, retrievals are not reported from conventional retrieval methods using measurements from passive sensors at the visible spectrum. Yet, observations from active sensors such as CALIOP are capable of detecting the presence of aerosol plumes above clouds. Sensors equipped with UV-absorbing channels, such as OMI, also have the capability to detect UV-absorbing aerosols above clouds. In an effort to evaluate above cloud aerosol data from CALIOP and OMI for aerosol assimilation, we found that above cloud smoke aerosol events, which are frequently found over the west coast of Africa during the Northern Hemisphere Summer, impact standard MODIS

cloud optical depth retrievals. We have quantified the effects and summarized our findings in a journal paper that will be submitted in the near future (Figure 1).

Surface particulate matter and especially particulate matter with particle diameters less than 2.5µm (PM2.5), have been routinely measured for use as a metric for both air quality monitoring and forecasts. While air quality studies have shown that satellite-retrieved AOD can be used as a proxy for PM2.5, surface PM2.5 measurements may also be applied to aerosol modeling studies. Using collocated MODIS, MISR, CALIOP and surface PM2.5 data, we have investigated the relationship between surface PM2.5 concentrations and satellite retrieved aerosol optical properties from both passive and active sensors. We have summarized our findings in a journal paper that will be submitted by/before 4 October.

Using the NAAPS-Fu-Liou system that was developed through last year's effort, we have estimated the sensitivity of existing satellite aerosol products to the current estimate of aerosol direct climate forcing through an ensemble-based method. The results of our findings were presented at the 2013 American Meteorological Society (AMS) annual meeting.

Satellite aerosol data product analysis:
Also from last year's efforts, we have finalized the study of applying MODIS cloud products for cloud-clearing of the MISR aerosol products. Very limited studies have attempted to explore the potential cloud contamination in MISR aerosol products. Only visible and near IR channels are available for MISR aerosol retrievals, which poses a great challenge to cloud screening using MISR observations alone. With the use of MODIS cloud products, which have additional channels that are sensitive to thin cirrus clouds, we have developed a cloud screening method using combined observations from both MODIS and MISR. We have also compared the MODIS-based MISR cloud screening method with the MISR Cloud Fraction Flag (CFF) based MISR cloud screening method. A journal paper has been submitted for this research effort (Figure 2).

Improvements to aerosol data assimilation schemes:
As the first step towards radiance assimilation, a GOES radiance simulator has been developed through coupling of the Community Radiative Transfer Model (CRTM) with NAAPS. The newly developed NAAPS-CRTM system will be used as a forward model for the GOES radiance assimilation scheme (Figure 3).

In alignment with an effort to improve NAAPS' forecasts to a finer resolution of $1/3° \times 1/3°$ (Latitude/Longitude) degree, we have developed an updated version of NAVDAS-AOD that accommodates this new resolution setting. A new package for constructing NAAPS aerosol climatological properties has also been developed for use in the 1/3 degree NAAPS/NAVDAS-AOD system. Both software packages were delivered to NRL for further evaluation.

Continuing from last year's efforts using DA-quality MODIS DT, CALIOP and newly updated DA-quality MODIS DB and MISR aerosol products, we have evaluated the impact of successively assimilating each product into NAAPS, using the assimilation of over water Terra MODIS DT product as the control case. The goal of this research is to understand the need for including new datasets to the existing operational aerosol assimilation data stream. The first part of the study has been recently submitted to a journal paper, and we are currently working on the second phase of the journal paper.

RESULTS

Evaluating the Impact of Aerosol Particles above Cloud on Cloud Optical Depth Retrievals from
MODIS (Alfaro-Contreras et al., 2013, in preparation for submission in the near future)
Using two distinct operational Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) cloud
optical depth (COD) retrievals (visible versus shortwave infrared, or standard versus supplementary),
we evaluate the impact that above-cloud absorbing aerosol particles have on standard COD retrievals.
As for all fine-mode aerosol particles, AOD values diminish sharply from the visible to the shortwave
infrared (SWIR) channels; thus we expect a much reduced above-cloud absorbing aerosol impact for
COD retrievals using the SWIR channels. Aerosol Index (AI) from collocated Ozone Monitoring
Instrument (OMI) aerosol products, and above-cloud AOD from the collocated Cloud-Aerosol Lidar
and Infrared Pathfinder Satellite Observation (CALIPSO) data were used to estimate above cloud
aerosol loadings from Africa over the Atlantic Ocean. In the smoke outflow region off the
southwestern coast of Africa, the frequency of occurrence for aerosol-above-cloud events often reaches
50% during the boreal summer. We find this above-cloud smoke introduces a low bias in COD of up
to 20% for the standard MODIS COD retrievals. No obvious bias is found over the Saharan dust
outflow region off northern Africa, as both MODIS visible and SWIR channels are affected by dust
aerosol particles and dust has very low absorption in the red to near IR wavelength region. This study
shows the necessity of accounting for the above cloud aerosol events for future studies using the
standard MODIS cloud products in biomass burning outflow regions, possibly with the use of OMI AI.

Impact of Data Quality and Surface-to-Column Representativeness on the PM2.5/Satellite AOD
Relationship for the Continental United States (Toth et al., 2013, in preparation for submission in the
near future)
Satellite-derived aerosol optical depth (AOD) observations have been used to estimate particulate
matter less than 2.5 μm in diameter (PM2.5). However, the representativeness of satellite-derived
AOD, surface aerosol particle mass concentration and AOD data quality should be considered before
using satellite-based observations as proxies for PM2.5 measurements in both operations and applied
research studies. Therefore, using purely measurement-based methods, we have explored the impact
of data quality in AOD data as well as the representativeness of satellite-derived AOD to surface
aerosol concentration on the PM2.5-AOD relationship for the Continental United States (CONUS)
using temporally and spatially-collocated datasets of PM2.5 and AOD retrievals from Aqua/Terra
Moderate Resolution Imaging Spectroradiometer (MODIS), Multi-angle Imaging Spectroradiometer
(MISR), and Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP). Our results show that
improving satellite AOD data quality, as done with data assimilation grade retrievals, general increases
correlations with PM2.5, but overall correlations are relatively low across the CONUS. Also, AOD
observed at 500 m above ground level (AGL) and below, as measured by CALIOP, is not very
representative of the total column AOD. However, surface AOD in the eastern CONUS is better
correlated with surface PM2.5 concentrations than in the western CONUS. Lastly, the best
correlations are found for dry mass CALIOP extinction at 200-300 m AGL and PM2.5, but additional
work is needed to address the ability of using actively-sensed AOD as a proxy for PM2.5
concentrations.

Critical evaluation of cloud contamination in the MISR aerosol products using MODIS cloud masking
products (Shi et al., 2013, submitted)
For the first time, using the Terra MODIS-based cloud screening methods, we evaluate the impacts of
cloud contamination on the Terra MISR aerosol optical depth (AOD) product. Our study, based on
one year of collocated MISR and MODIS data, suggests that cloud contamination exists in both over-

water and over-land MISR AOD data with heavier cloud contamination occurring over the high latitude southern hemispheric oceans. Globally averaged, our study shows that thin cirrus cloud contamination introduces a possible ~0.01 high bias for the over-water MISR AOD retrievals. Over the mid to high latitude oceans and Southeast Asia, this number increases to 0.015-0.02, with very high biases found in individual retrievals. This study also suggests that cloud-clearing methods using observations from MISR alone, which only utilizes visible and near infrared channels, may not be sufficient. Measurements from MODIS can be applied to assist cloud-clearing of the MISR aerosol retrievals. Indeed, cloud screening algorithms based on the multi-sensor approaches are feasible and should be considered for current and future satellite aerosol studies.

Evaluating the Impact of Multi-Sensor Data Assimilation on A Global Aerosol Particle Transport Model. Part I: Characterizing the Sequential Assimilation of Quality-Assured Satellite Aerosol Products (Zhang et al., 2013a, submitted)
By sequentially evaluating quality-assured MODIS Dark Target (DT), MODIS DeepBlue (DB), MISR and CALIOP aerosol products into NAAPS, the impact of multi-sensor data assimilation on aerosol optical depth (AOD) analysis and forecast skill is characterized using ground-based Level 2 AErosol RObotic NETwork (AERONET) datasets. Model improvement is greatest with the combined use of Terra and Aqua MODIS DT products, at both global and regional scales. Incremental improvements are identified, as a function of data density, over regions such as the Saharan desert when adding MISR and MODIS DB products.   The inclusion of CALIOP data has an insignificant impact on the NAAPS 00-hr analysis. Improvements from lidar profiling, however, increase through the model forecast cycle. After assimilating all available datasets, the accuracy of both over-ocean and over-land NAAPS AOD analyses correlates favorably with that of a composite satellite AOD product built from MODIS and MISR. Relatively large root mean square error (RMSE) values, exceeding 0.1, are found over East Asia and North Africa for both the NAAPS analysis and satellite AOD data, indicating that further refinements are needed for satellite aerosol products for these two regions. Similarly, a low correlation is found between NAAPS and AERONET over Australia, even with the use of all available satellite aerosol products, due to the presence of isolated biomass burning plumes. This suggests that a more detailed regional study is necessary in some critical regions.

Sensitivity of Aerosol Climate Forcing to the Existing Satellite Observations (Zhang et al., 2013b, presented at the 2013 AMS annual meeting)
Aerosol direct and indirect climate forcing have been extensively studied using numerical models and satellite and ground based observations. Due to their close connection to atmospheric radiative properties, and their high spatial and temporal coverage, satellite observations have been used for model evaluations and estimations of aerosol climate impacts. However, satellite observations, including column integrated parameters, such as aerosol optical depth, and vertical distributions, such as aerosol and cloud profiles, from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), are subject to uncertainties of their own. It is therefore necessary to study and propagate the sensitivity of climate studies from the known uncertainties in satellite aerosol retrievals. In this study, sources of error in passive and active satellite observations, which affect climate forcing studies are explored. Examples of such issues include cloud contamination, lower boundary conditions, and calibration. Major discrepancies among satellite aerosol products are studied, such as the elevated high aerosol optical depth zone reported by Moderate Resolution Imaging Spectroradiometer (MODIS) and Multi-angle Imaging SpectroRadiometer (MISR) but not seen in data from several other sensors. Finally, an ensemble method was applied for studying aerosol climate forcing using a combination of passive and active sensor observations with a chemical transport model through coupled 2D/3DVAR data assimilation.

<u>Developing a NAAPS based radiance simulator using CRTM (Figure 3).</u>
In collaboration with Dr. Mark Liu from NOAA, we have incorporated aerosol optical properties, required for NAVDAS-AOD, into the Community Radiative Transfer Model (CRTM) and further developed a coupled NAAPS-CRTM model for simulating GOES radiance. The CRTM is used due to its fast computational speed for both radiance and Jacobians. The GOES radiance simulator will be used as a forward model for the on-going GOES radiance assimilation efforts. An example of the GOES-radiance simulator is shown in Figure 3.

<u>Developing a finer spatial resolution NAVDAS-AOD for operational aerosol data assimilation</u>
In continuation from last year's effort, collaborating with NRL scientists, we have developed a new version of NAVDAS-AOD at the spatial resolution of 1/3°×1/3° (Latitude/Longitude) degree for use in future aerosol forecasts with improved spatial resolution. The system is currently in evaluation at NRL for transition to operations.

IMPACT/APPLICATIONS

The 1/3° resolution NAVDAS-AOD will be implemented for operational aerosol forecasts. Findings from our above-cloud aerosol studies highlighted the needs for considering above-cloud aerosol events in future passive satellite based cloud optical property products.

TRANSITIONS

The 1/3° resolution NAVDAS-AOD, and the latest version of software packages for constructing DA-quality MISR and MODIS DB products for aerosol assimilation have been transitioned to NRL for further evaluation.

RELATED PROJECTS

Graduate student Yingxi Shi is supported by the NASA Earth and Space Science Fellowship Program. Graduate student Ricardo Alfaro-Contreras is also supported by a UND Space Grant. The MISR cloud clearing study is also partially supported by a UCAR project (Z13-95924).

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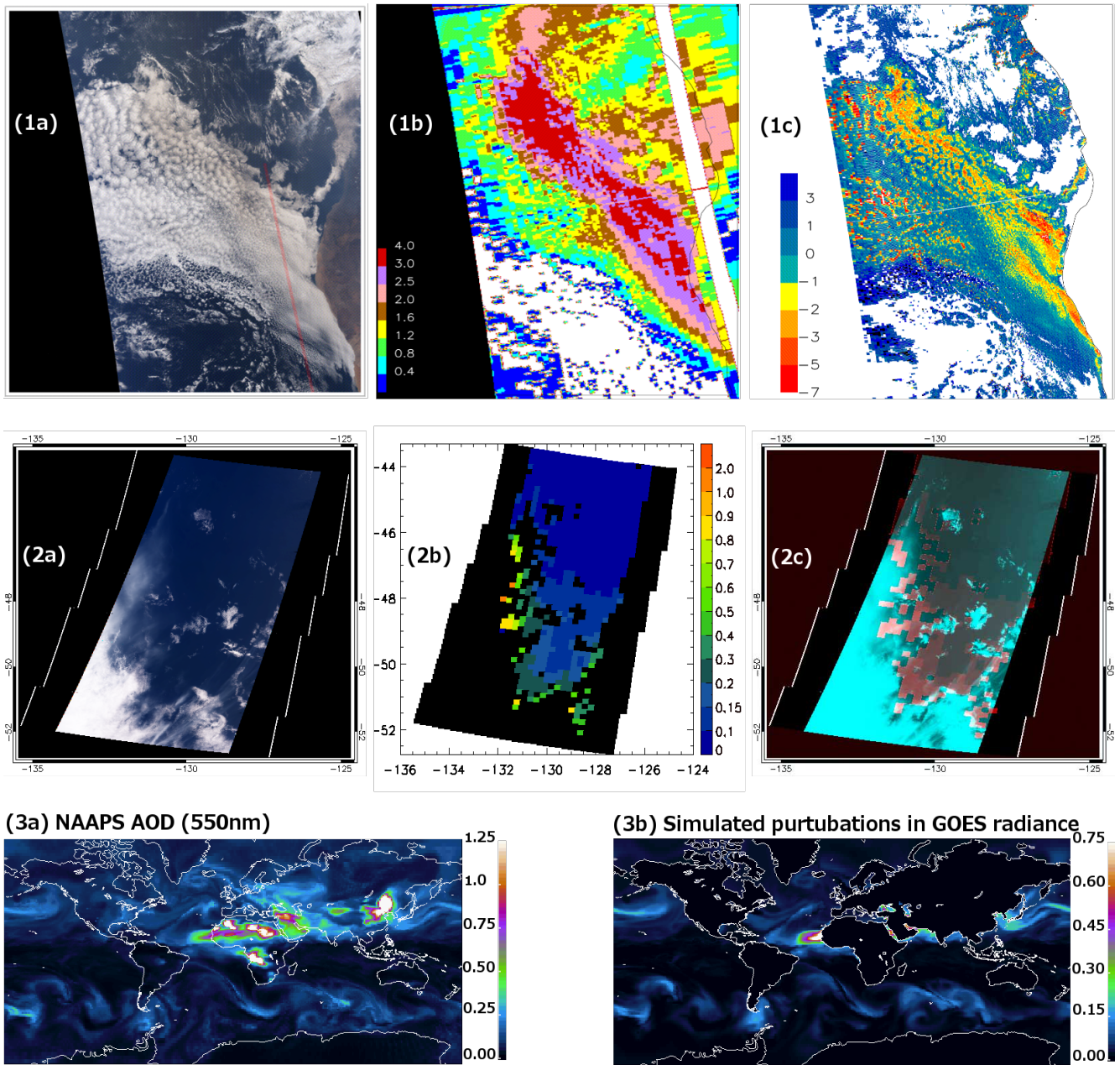
Figure 1a.) Aqua MODIS true color image on 4 August 4 2007 off the southwest coast of Africa. b) The same domain as a), but for OMI Aerosol Index (AI). c) Differences between cloud optical depth (COD) using the standard and supplementary MODIS COD retrievals showing the potential aerosol contamination in the standard MODIS COD data.

Figure 2. A case study on January 3rd 2007, over the remote oceans (44° to 52° S and 124° to 136° W), a) RGB image created using the MISR Near IR, green and blue bands, b) MISR AOD over the case study region, c) Overlay of a) on b) where the intensity of red is correlated with the magnitude of the AOD. Cloud contamination to the MISR AOD retrieval is apparent as most of the highest AOD retrievals (AODs greater than 0.3) are located within cloudy regions and higher AOD values of around 0.2 to 0.3 are found near the edge of clouds.

Figure 3. Estimated aerosol induced perturbations in visible, over water, cloud free sky GOES-15 radiance using a coupled NAAPS, NOGAPS and CRTM system. a) NAAPS AOD for June 1, 2007 (00UTC). b) Aerosol induced perturbations in simulated over water visible GOES radiance (mW/m^2.sr.cm^{-1}). Constant solar zenith angle (0°) and viewing angle (30°) were assumed for demonstration purposes only (Figure 3b doesn't represent the true spatial coverage from GOES-15).

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